Marine Water Surface Reflectance

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LONG-TERM GOALS

Our long-term goal is to develop improved autonomous observation systems and analytical capabilities for describing the distributions and activities of marine microbes in relation to their physical, chemical and optical environment in support of multidisciplinary, data-assimilating predictive models of optical and biological processes in the world ocean.

OBJECTIVES

Our primary objectives are:

- To develop and test new interdisciplinary sensor arrays on a variety of *in situ* platforms to describe biological variability in relation to the optical, physical and chemical environment of the ocean; and

- To use data from these sensor systems in multidisciplinary models of physically and chemically driven ocean biology.

APPROACH

Data from deployments of coastal ocean observatories and research cruises are used to develop and evaluate models and bio-optical algorithms for estimating optical and biological properties of surface waters using measurements from a variety of optical instruments. An extensive program of sampling from research vessels at our coastal observatories provides a large set of date for development and validation of bio-optical models for case 2 waters.

Several of our bio-optical analyses utilize chlorophyll fluorescence — sun-induced, or stimulated by a variety of fluorometers — to describe variability in the biomass or physiological status of phytoplankton. Consequently, we study the environmental influences on chlorophyll fluorescence in controlled laboratory experiments using different taxonomic groups of phytoplankton. The research

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includes a careful characterization of Satlantic's new Fluorescence Induction and Relaxation (FIRe) fluorometer, to define clearly its potential and limitations for describing phytoplankton physiology under a broad range of conditions.

More broadly, we are working within our own research group and with others in the ocean-observation community to develop effective new ways to make ocean observatory data easily accessible to a broad range of users (Cullen 2006a). Also, we are developing new collaborations and approaches to facilitate advanced interdisciplinary, observation-based modeling of the ocean (Rothstein et al. 2006).

WORK COMPLETED

Optical moorings and ground-truthing in coastal waters. We continued to support the operations of four optical mooring systems in coastal waters of Nova Scotia. These moorings include hyperspectral observations of upwelling radiance, and downwelling irradiance; they also include multi-spectral K-chains, physical observations (currents, temperature, salinity profiles) and observations of meteorological variables. The systems communicate via wireless broadband to shore based computers at Dalhousie. Three moored systems have functioned very well since 2002 (except during winter haul-out and some interruptions in 2005), providing real time data supported by nearly weekly sampling for ground-truth data: vertical profiles of irradiance, fluorescence, spectral backscatter, dissolved and particulate absorption; and samples for chlorophyll, HPLC pigments, nutrients and particulate and dissolved absorption (Kirchhoff et al. 2006). A new optical profiler has been assembled and deployed for studies of thin layers; it includes fast sensors for temperature and conductivity, plus oxygen, backscatter, three types of fluorescence, a Satlantic in situ nitrate sensor and a WET Labs ac-s in situ spectrophotometer. A fourth mooring is deployed in Ship Harbour, NS, for a study of optical monitoring near aquaculture sites. It has operated with during summer-fall since 2003, backed up with regular sampling.

New system for delivering data from ocean observatories. A team of programmers has made several significant technical accomplishments in the development of the Center for Marine Environmental Prediction (CMEP) data access and visualization system (http://cmep-av.ocean.dal.ca/). These include an interface with Google Earth with layers showing locally processed satellite imagery and cell-phone access to real-time data (Figure 1).

Incorporation of remote sensing. A new addition this year has been the ingestion and statistical assimilation of satellite observations of sea-surface temperature and surface chlorophyll. These data are made available on the same grid as used in numerical models; as well, they are reformatted for distribution and display using the GoogleEarth package.

Development an inverse model of ocean color and attenuation that retrieves estimates of phytoplankton biomass in case 2 waters. A manuscript describing the model of Huot et al. (2006) was submitted and favorably reviewed; final revisions should be completed very soon. Meantime, Susanne Craig and her colleagues (2006a,b) have completed a thorough diagnosis of the Huot et al. model, which performs quite well in our case-2 coastal waters because it relies on sun-induced chlorophyll fluorescence rather than on the detection of the phytoplankton absorption signature, which is problematic in the presence of chromophoric dissolved organic matter (CDOM); errors that do persist can be related to the effects of nutrition and community composition (e.g., diatoms) on the quantum yield of fluorescence emitted by phytoplankton.

Characterization of a new fluorometer and development of protocols for calibration. Audrey Barnett and colleagues completed the first stage of a careful characterization of Satlantic's FIRe fluorometer (Barnett et al. 2006) and worked with Satlantic to enhance system functionality.

Synthesis. John Cullen has been synthesizing results from these and prior studies of fluorescence and will present an overview at the Ocean Optics meeting in Montreal (Cullen et al. 2006).

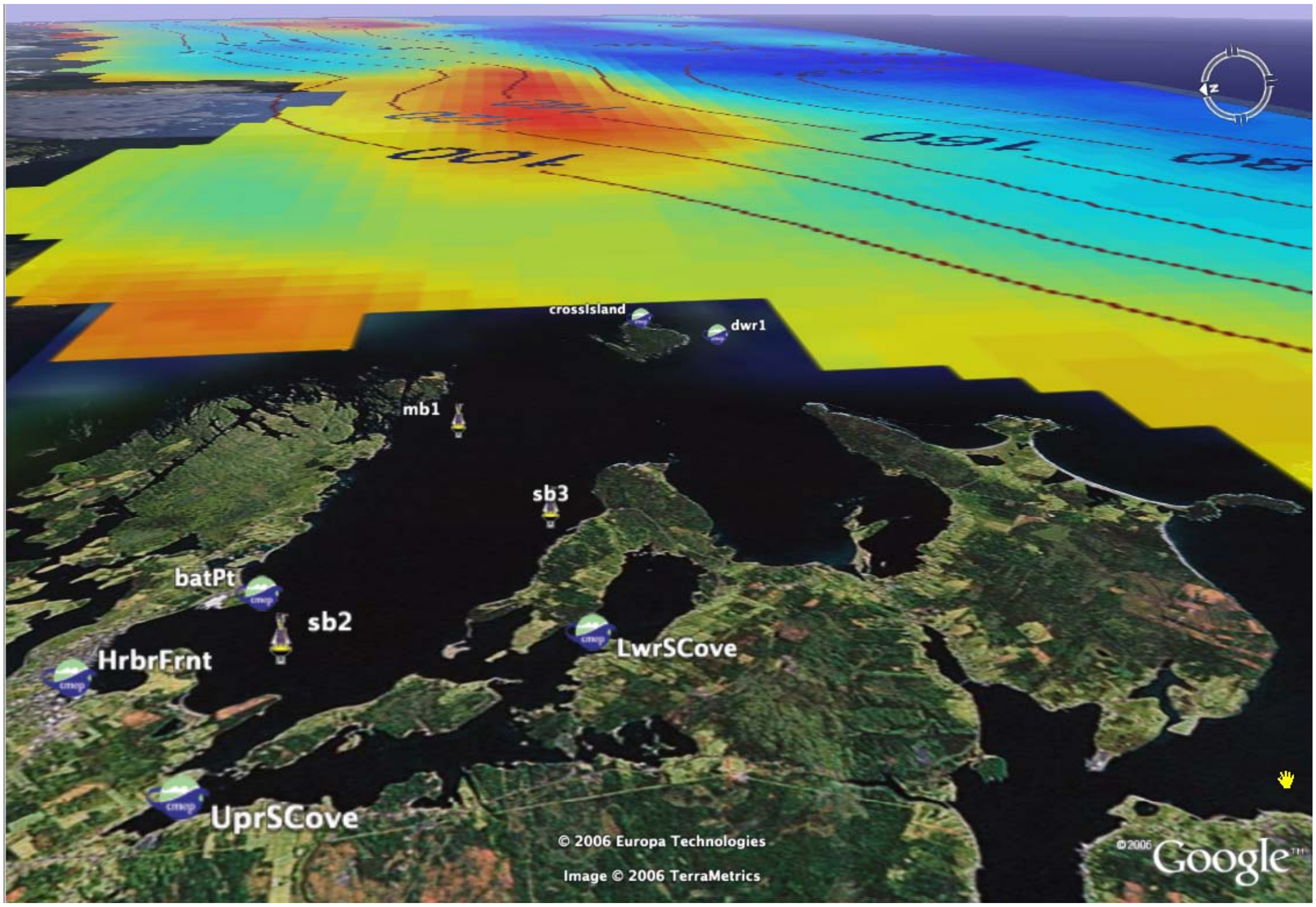

Figure 1. Image of Lunenburg Bay and adjacent waters, viewed using Google Earth and showing icons of moorings and other sensors, each of which can be clicked to access real-time (when deployed) and archived data. Real-time data can also be accessed by cell phone. Surface chlorophyll from the MODIS satellite sensor is presented as a layer; it can be switched to sea-surface temperature. Satellite images are updated daily as available. See http://cmep-av.ocean.dal.ca/.

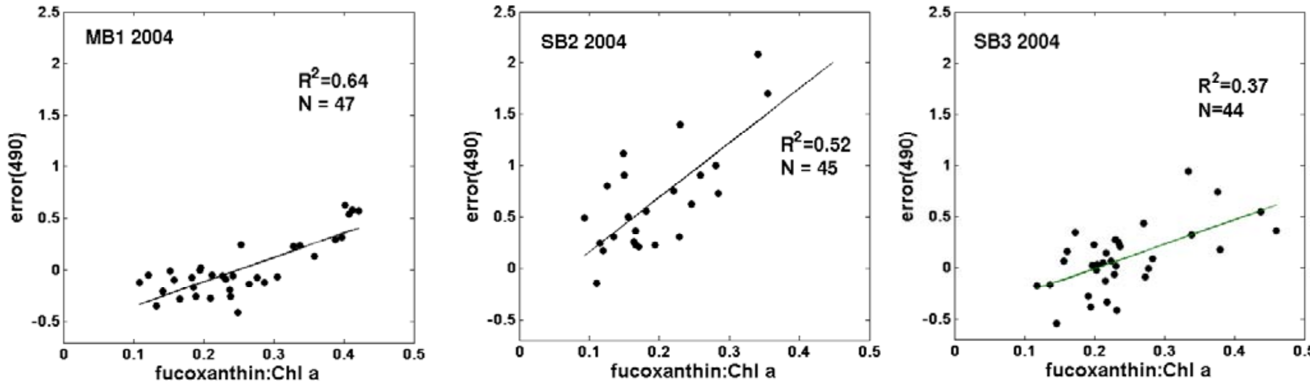

Figure 2. Diagnosis of errors in a fluorescence-based inverse model of ocean color and attenuation. Error in the retrieval of phytoplankton absorption coefficient at 490 nm is plotted vs the ratio of fucoxanthin to chlorophyll* a *for three stations from Lunenburg Bay. Supporting analysis suggests that errors are due to variability in the quantum yield of sun-induced fluorescence: relatively high yields, hence overestimations of phytoplankton absorption, are associated with diatoms (high fucoxanthin:chlorophyll) and nutrient enrichment (center graph: inshore station SB2).

RESULTS

Our efforts to develop observation-based interdisciplinary modeling systems advanced on two fronts. Maud Guarracino and Michael Dowd continued to make progress on an assimilative biological-physical forecast system that will be implemented in Lunenburg Bay next year. This year, Guarracino fully developed her modeling system and conducted several numerical experiments to test hypotheses about dominant influences on biological dynamics in the bay (Guarracino et al. 2006). More broadly, we continued to develop frameworks for interdisciplinary global modeling (Rothstein et al. 2006), including the development of a transformative design for assimilative modeling of observable optical proxies for biological properties (Cullen 2006a).

The inverse model of Huot et al. (2005, 2006) was further examined and refined prior to manuscript submission. A shading correction was implemented and retrievals of chlorophyll concentration were compared to a conventional ocean color algorithm, OC4V4, which cannot function in our CDOM-dominated waters, even with a local parameterization. Our inverse model effectively retrieved chlorophyll concentration when applied to an independent dataset from the case 2 waters of Lunenburg Bay — r=0.76, n=93, with a mean absolute percent error (MAPE) of 24%; this is better than the OC4V4 algorithm performed on NASA's NOMAD global validation dataset for this case 1 algorithm, when restricted to a comparable range of chlorophyll (r=0.67, n=384, MAPE=51%). Consequently, our new model represents a significant advance in the optical detection of phytoplankton in case 2 waters.

Suzanne Craig and colleagues (Craig et al. 2006a,b) have followed up on the study by Huot et al. by exploiting our substantial ground-truth data set to look for factors that might have contributed to errors in inverse model retrievals of phytoplankton absorption. The analysis showed that parameterization of the model seems to be robust, and that the source of error is likely the fixed model function describing the quantum yield of fluorescence as a function of irradiance. Errors were correlated with a pigment-based diagnostic of diatom dominance, and also with location of the buoys collecting data (likely an effect of nutrition). This suggests strongly that variations in sun-induced fluorescence yield are

providing useful information on nutrition and community composition (Figure 2). Interestingly, higher fluorescence yields are associated with nutrient-rich conditions, contrary to the prevailing, but tentative working hypothesis.

Careful reanalysis of our data from an optical drifter in the Bering Sea (Christina Schallenberg) confirms that fluorescence yield can vary tenfold over a week or less, unlike coastal Nova Scotia, where fluorescence yield seems to vary by less than a factor of 4 over several months. The cause is nonphotochemical quenching of fluorescence (NPQ), a process that likely dominates variability of sun induced fluorescence yield in the open ocean. However, very little is known about the environmental influences on NPQ, so much laboratory research is needed; the thesis research of Audrey Barnett (2005) addressed this question directly and yielded new and useful parameterizations of the process and its relationships to nutrition and light history of diatoms in culture.

IMPACT/APPLICATIONS

Coastal observatories. Our coastal observatory project has entered its fifth year, and the hard work and learning experiences are paying off as the data management and presentation systems become more and more efficient and the partners involved recognize more clearly exactly what it takes to run a coastal observatory. This information is critical in planning for new systems and an integrated ocean observing strategy. For example, the observatory was used as a live demonstration for the National Oceanic and Atmospheric Administration in Washington, D.C. to help establish our technology as a platform for the U.S. Integrated Ocean Observing System. Satlantic's technical deployments coupled with Dalhousie's effort in establishing and maintaining real time web, Google Earth and Wireless Meta Language (WML) sites to visualize data from the system is key to this demonstration.

Information systems. Cullen was invited to present a Plenary Address at the Ocean Sciences Meeting in Honolulu (Cullen, 2006a). Many of the 3000+ registrants attended the talk, and his description of the future of ocean observations, and their use in "Ocean VISION" — a Virtual-reality Information System and Integrated Ocean-observation Network — was very well received. Copies of the presentation were given, on request, to representatives of The U.S. Office of Naval Research, NSF, NASA and ocean observing networks (MBARI, GoMOOS, LEO-15, SO-COOL, and NANOOS). The presentation has led to contacts with Google and is being used in promotion of the nascent International Coalition of Ocean Observing Laboratories (I-COOL), of which we are a founding member, along with the Coastal Ocean Observation Laboratory of Rutgers University. Our data access and visualization group, CMEP-AV (led by Sean Hartwell) has entered a cooperative agreement with the Monterey Bay Aquarium Research Institute for innovative data base development.

Fluorescence. Although our principal objectives in studying fluorescence are to detect phytoplankton and to describe their physiological properties, we spend much of our time trying to ensure that the measurements are made properly and analyzed effectively, with careful consideration of the possible influences of errors — e.g., from inadequate consideration of blanks, oversimplified optical models, or the application of results from one system for measuring fluorescence (e.g., benchtop fluorometers using dark adaptation) to another (sun-induced fluorescence). It is difficult to quantify our impact, but certainly there is some. John Cullen was recently invited to an international meeting on Chlorophyll Fluorescence in Aquatic Sciences in the Czech Republic and he continues to serve on Alliance for Coastal Technologies Fluorometer Performance Verification Technical Advisory Committee.

Interdisciplinary modeling. In both the article describing PARADIGM, the Partnership for Advancing Interdisciplinary Global Modeling (Rothstein et al. 2006) and the Plenary Address at the Ocean Sciences Meeting, Cullen described a vision for the future of interdisciplinary global modeling. This vision includes the ultimate integration of marine microbial genomics research with observation-based ocean forecasting and climate studies. His potential for helping to guide this coming revolution in marine science was recognized with an invitation to be a visiting faculty member for the Agouron Institute Hawaii Summer Course, "Microbial Oceanography: From Genomes to Biomes" (Cullen, 2006b). It was an opportunity to interact with future leaders in ocean science (the students, who were selected through competition) and the cutting-edge researchers who are bringing genomics research to oceanography today.

TRANSITIONS

The technical approach used in the construction and deployment of the mooring arrays has been useful in other related deployments in New Hampshire, Newfoundland, and Morro Bay.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the focus of support for Cullen's research activities. Funding for complementary projects, such as this ONR program, are highly leveraged by the research partnership and associated grants.

2) A research project on interdisciplinary marine environmental prediction in the Atlantic coastal zone (Canadian Foundation for Climate and Atmospheric Sciences) is a major source of support for the field program in Lunenburg Bay and the development of optical data products for use in models of the Bay. The Lunenburg Bay infrastructure was funded by the Canada Foundation for Innovation, the Nova Scotia / Canada Cooperation agreement, and several other partners. It supported the initial development of the Data Access and Visualization project.

3) The Institute of Marine Biosciences, National Research Council of Canada is a major partner in our study of optical detection of biological variability near an aquaculture site in Ship Harbour, Nova Scotia. The emphasis is on detection and prediction of harmful algal blooms. The comparison of Ship Harbour with Lunenburg promises to be very helpful in the development and testing of hypotheses about optics and phytoplankton dynamics, which seem to be quite different in the two sites.

4) Cullen is a member of PARADIGM (The Partnership for Advancing Interdisciplinary Global Modeling; a NOPP project). The project supports some analysis of data from our coastal observing system with an aim to develop and evaluate novel optical data products that might be used in global data assimilation models of ecosystems dynamics. It is the focus of the recent publication by Rothstein et al. (2006) in a special issue of *Oceanography Magazine* on Advances in Computational Oceanography. Cullen's strong role in preparation of that paper is recognized with second authorship, behind project leader Lew Rothstein.

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PUBLICATIONS

The following manuscripts resulted in full or in part from this contract:

Babin, M. Roesler, C.S. and J.J. Cullen, J.J. (eds). 2006. *Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling*. UNESCO, Paris [in press; refereed].

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Barnett, A.B., 2005. Nonphotochemical quenching of fluorescence as a diagnostic of light history and nutrient stress in the diatom *Thalassiosira pseudonana.* M.Sc. Thesis, Dalhousie University.

HONORS

Cullen was appointed the Killam Chair in Ocean Studies at Dalhousie University.

Cullen was appointed a Fellow of The Oceanography Society.

Cullen's Industrial Research Chair in Environmental Observation Technology was also renewed for a third, five-year term.